AFOSR-TR-97-0591

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE

3. REPORT TYPE AND DATES COVERED
Final 15 Mar 94 to 31 Aug 97

4. TITLE AND SUBTITLE
Materials Engineering Novel Semiconductor Structures

5. FUNDING NUMBERS
61101F
2305/DS

6. AUTHOR(S)
Professor Khurgin

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
The Johns Hopkins Uiversity
Homewood Research Admin
Charles and 34th Street
Baltimore, MD 21218

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR/NE
110 Duncan Avenue Room B115
BNo
Bolling AFB, DC 20332-8050

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
f49620-94-1-0191

11. SUPPLEMENTARY NOTES

19971119 063

12a. DISTRIBUTION/AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

13. ABSTRACT *(Maximum 200 words)*

This research has focused on using the methods of "band-gap engineering" to improve various electronic and optical properties of materials. From and experimental point of view, it has achived the capability of routinely performing photoluminescinece, photo condutivity and photoluminesence excitation measurement at the JHU faciltites. Among the most important theoretical results are advances in intersubband lasers and raman oscillators, especially a new "inverted effective mass" scheme. A theory of optical generation of THz radiation in bulk semiconductors and QW's has been developed to explain the experimental results of other groups. A major achievement has been the development of a rigorous theory for a group of phenomena commonly known as "lasing without inversion:. For the first time we have developed expressions for threshold and slope effciency and have come to conclusion that at least for our case of interest-quantum-confined semiconductor structures "lasing without inversion" does not offer any advantage over more conventional schemes.

14. SUBJECT TERMS

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFEED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18

DTIC QUALITY INSPECTED 3

Final Report on the Research Grant
F496209410191
Material Engineering of Novel Semiconductor Structures

Submitted to
The US Air Force Office of Scientific Research
Program Manager: Dr. Alan E. Craig
Project Period: March 16, 1994 - March 15, 1997

Principal Investigator:
Dr. Jacob B. Khurgin
Professor,
Department of Electrical and Computer Engineering
The Johns Hopkins University
Baltimore MD 21218

1 Introduction

Current research effort had been initiated by the AFOSR in May 1989 and since then it had been renewed twice. The main effort of the proposal has always been to conduct cutting edge theoretical and experimental research in the rapidly developing area of semiconductor nanostructures with an eye on potential applications in the areas of communications and information processing. In the mid-1980's semiconductor quantum wells (QW's) and superlattices (SL's) have been shown to possess electronic and optical properties dramatically different from those of bulk semiconductors. Immediately a number of practical proposals for novel electronic and electro-optical devices have been put forward. These devices included QW lasers, infrared detectors, high mobility transistors, tunneling devices and electro-optical modulators.

This
Our group's research has ~~been~~ focused on using the methods of "band-gap engineering" to improve various electronic and optical properties of materials. For instance, we have pioneered use of asymmetric QW's for second harmonic generation and other second-order nonlinear processes, we introduced the concept of the four-level intersubband laser, which contributed to the development of Quantum-Cascade Lasers. Idea of asymmetric SEED device was also suggested by our group. We also studied nonlinear optical processes in p-doped and type-II heterostructures, as well as the use of heterostructures for generation of THz microwave pulses. The emphasis of our work has always been placed on evaluating the feasibility of practical military and commercial applications.

In this proposal we first give a brief review of the major achievements of the third stage of our effort (1994-1996) and then outline the directions of future research.

We discuss the results of the research conducted in the course of more than three years elapsed since the last renewal of the project. From an experimental point of view, ~~we have~~ it has achieved the capability of routinely performing photoluminescence, photo-conductivity and photoluminescence excitation measurement at the JHU facilities. Femtosecond studies can be now conducted in collaboration with Dr. Y. Ding group at Bowling Green University, where a number of exciting experiments on the dynamics of optical processes involving interface islands have been carried out. We have also performed some experimental work in collaboration with NASA Goddard Space Center devoted to generation of $100\mu m$ radiation in QW's.

are
Among the most important theoretical results ~~we~~ describe advances in intersubband lasers and Raman oscillators, especially a new "inverted effective mass" scheme. ~~We have also developed~~ A ~~a~~ theory of optical generation of THz radiation in bulk semiconductors and QW's, ~~and~~ explained the experimental results of other groups. A major achievement has been the development of a rigorous theory for a group of phenomena commonly known as "lasing without inversion". For the first time we have developed expressions for threshold and slope.

has been developed to.

efficiency and have come to conclusion that at least for our case of interest - quantum-confined semiconductor structures "lasing without inversion" does not offer any advantage over more conventional schemes. We also proposed a number of novel optoelectronic devices based on localization/delocalization transitions in superlattices and a fundamentally novel concept of low threshold lasing using image charges in quantum dots. We have fully developed a concept of using cascaded nonlinearities in vertical cavity structures to perform a number of standard nonlinear operations.

2 Main results

The work had been performed in the following areas:

1. **Intersubband lasers**

   This work have been focused in four major areas - influence of the ionized and neutral impurities on the inter-well tunneling in quantum wells, comparative analysis of the intersubband lasers and Raman oscillators, prospects for surface-emitting lasers based on the effective mass reversal in the valence bands, and, finally on feasibility of ultra-low threshold quantum-box lasers based on image charges.

   (a) *Comparative Analysis of Optically-Pumped Intersubband Lasers and Intersubband Raman Oscillators.*

   A new tunable source of the far infrared radiation based on the phenomenon of intersubband stimulated electronic Raman scattering in semiconductor quantum wells has been proposed by us. The threshold, efficiency, and tunability range of the proposed Raman oscillator have been evaluated and found to constitute an improvement over those of the optically-pumped intersubband laser
   The results have been reported at the CLEO-95 conference and published in the Journal of Applied Physics.

   (b) *Influence of the ionized impurities on the tunneling rates in semiconductor quantum wells*
   We have studied theoretically the impurity assisted tunneling in the multiple quantum wells structures. We have shown that by strategically placing the impurities, it is possible to change the tunneling rates by as much as two orders of magnitude. This opens an opportunity of "engineering" structures with "customized" tunneling rates suitable for achieving the intersubband population inversion and lasing. Currently an experimental effort is under way.
   The results have been reported at the CLEO-95 conference and published in the IEEE Journal of Quantum Electronics

   (c) *Silicon-based surface-emitting intersubband lasers based on the effective mass reversal in valence band of semiconductor quantum wells.*
   We introduced a fundamentally new concept of the mid-IR lasers. This concept combines advantages of conventional semiconductor lasers and intersubband lasers. The concept is based on the change of sign in the effective mass due to valence subband mixing. This concept will be thoroughly investigated and hopefully implemented in the next few years.

(d) *Novel type of the quantum box intersubband laser based on Stokes shift by image charges.*

We considered theoretically a novel lasing scheme in semiconductor quantum boxes. Ultra-low threshold pumping power can be obtained thanks to development of images charges in surrounding layers. The impact of the intersubband lasing have been stressed. It had been show, that the scheme can also operate as a "phonon-pumped laser".

The results have been reported at two conferences and published in the Applied Physics Letters.

2. Generation of the THz radiation in the bulk semiconductors and quantum wells.

(a) *Optical Rectification and Terahertz Emission in the Semiconductors Excited Above The Bandgap.*

A rigorous theory of the optical rectification in the zinc-blende semiconductors has been developed. This theory combines the bonding orbitals representation of the electrons in the semiconductor with the band structure representation. It has been shown that when the semiconductor is excited above the absorption edge there is a strong resonant enhancement of the optical rectification signal and connected with it emission of the terahertz radiation. Both the magnitude and the temporal characteristics of this signal are closely related to the intraband relaxation processes in the valence band.

The results are reported in Journal of Optical Society of America B

(b) *Dispersion and Anisotropy of the Optical Rectification in the zinc-blende quantum wells.*

It has demonstrated theoretically that the optical rectification and difference-frequency generation nonlinear coefficients, known to exist in the asymmetric quantum wells for certain directions of growth do not vanish even in the symmetric quantum wells. The dispersion and anisotropy of the optical rectification coefficient is evaluated and the magnitude of it is found to be one order larger than for the bulk zinc blende materials. This dramatic change has shown to be caused by the lifting of the valence band degeneracy. Practical applications for generating terahertz radiation are considered.

The results are reported in Journal of Optical Society of America B

(c) *Generation of low-frequency current and terahertz radiation using $\chi^{(3)}$ in semiconductors.*

We have investigated theoretically the difference frequency mixing in the bulk zinc blende or diamond structure semiconductors and shown that a lower-frequency (DC - 10THz) directional photocurrent and voltage can be generated as a result of the third-order nonlinear interaction. Practical applications for the phase-sensitive detector have been considered.

Results are reported in the International Journal of Nonlinear Physics and presented at the QELS conference.

(d) *Current-induced second harmonic generation in semiconductors*

Direct current in semiconductor has been theoretically shown to be capable of doubling the frequency of the incoming optical radiation. The second order susceptibility, proportional to the current is calculated to be in the $10^{-14} - 10^{-13} m/V$ range. Applications of the novel phenomenon in probing and mapping of the current in semiconductor devices were considered.

3. Novel phenomena associated with localization and delocalization in the semiconductor superlattices.

(a) *Optical Wannier-Stark Effect*

rm We have discovered a novel effect, consisting of optically-induced effective mass change due to the change in the degree of localization in the semiconductor superlattices. Thorough theoretical investigation has revealed the interest in physics of this effect. Possible application as a non-absorbing differential light detector/switch is considered.

The results have been reported in the Applied Physics Letters

(b) *Controlled Superluminescence in Semiconductor Superlattices*

Radiative recombination of the excitonic states in semiconductor superlattices in the presence of the electric field has been studied theoretically. It has been shown that when the electron-hole Coulomb interaction energy exceeds the miniband width, a coherent excitonic state is created whose oscillator strength surpasses the oscillator strength of a single quantum well by orders of magnitude. We also demonstrated that a small external field can split the coherent state into isolated well states and thus severely deplete the oscillator strength of the exciton. This

opens the possibility of modulating and switching of super-radiance in semiconductor devices.

The results have been reported in the Applied Physics Letters

4. **Prospects for inversionless lasers in semiconductor structures**

A rigorous density-matrix-based theory of lasing based on optically-induced or autoionization-induced coherence between the levels has developed. For the first time the balance equations have obtained, and the conditions for lasing threshold are established as a function of pumping strength and relaxation rates. Connection between the lasing without inversion and Raman and parametric processes was clearly established. The main conclusion is that true CW lasing without inversion can indeed be obtained but only in a system where pumping and relaxation rates are favorable for attaining either conventional lasing with population inversion or for the stimulated Raman oscillations (Stokes and Anti-Stokes). Practical implications of it, especially for the intersubband lasers have been discussed.

Results have been published in Physical Review A and IEEE Journal of Quantum Electronics.

5. **All-Optical Switching and Frequency-Conversion Components Based on Cascaded Second-Order Nonlinearity**

Many nonlinear optical phenomena depend on a nonzero value for the third-order nonlinear susceptibilities, $\chi^{(3)}$, which is very small in most conventional materials. Recently, it has been found that a cascaded second-harmonic generation (SHG) scheme could be used to effectively produce an effective third-order nonlinearity . The most effective SHG scheme uses surface-emitting SHG confined to a waveguide structure . Efficiency can be further improved by using the large second-order optical susceptibilities found in asymmetric quantum wells where the sign of $\chi^{(2)}$ can be modulated .

We proposed a family of all-optical switching devices and frequency conversion components based on the cascaded second-order nonlinearity. All of these devices are based on the large $\chi^{(2)}$ of the asymmetric QW's and characterized by low absorption, high efficiency, versatility, and the ability to be integrated with other opto-electronic components on the same chip. The technological steps involved in the fabrication of the devices are practically the same ones involved in fabrication of VCSEL's and DFB lasers.

The proposed devices are:

- Optical limiter
- Self-phase modulator
- Optical frequency shifter
- Optical parametric oscillator
- Optical phase conjugator
- Nonlinear directional coupler

The results are reported in a number of papers.

6. **Novel devices based on moving gratings in photoconductors**

We have shown that the autocorrelation function of mode-locked laser pulses can be measured by interfering a pulse with its time-delayed replica in a conventional photoconductor to generate a pulsating grating that can be represented as a superposition of moving gratings. The resonance current peak resulting from matching the carrier drift velocity to the velocity of one of the grating components is proportional to the autocorrelation function. Unlike conventional autocorrelators, the proposed method uses no nonlinear effects and thus can be utilized for measuring weak pulses.

The results are published in APL.

7. **Demonstration of novel pressure and strain sensors**

The recent trends in materials engineering put strong emphasis on the development of intelligent processes and of so-called smart materials. Sensing systems based on such materials invariably require efficient and inexpensive pressure/strain sensors which are immune to the impacts of environmental influences and easily integrated with signal processing circuitry.

We have proposed and demonstrated novel concepts for pressure/strain measurement based on both bulk and quantum well semiconductor structures.

All of our structures are pressure-to-electrical transducers dependent on mobility/conductivity changes occuring in current channels so that the extensive development of field-effect-transistor (FET) technology can be applied with little modification. This is in contrast to the recently developed Si micromechanical sensors which require difficult and elaborate processing techniques commonly associated with diaphragm-based sensors [?]. While all of our designs offer good sensitivity, quantum well devices render additional advantage of being fully "differential" and thus can be designed to be insensitive to temperature fluctuation and other perturbing factors.

The results are published in APL.

8. Development of the coherent microscopic theory of the cascaded processes in nonlinear optics.

A general microscopic theory treating cascading of a wide range of nonlinear optical processes as a collective effect is developed. Important practical implications are discussed.

The results are published in JOSA B

3 Related papers published in 1994-1997

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